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ABSTRACT

Background: Patients with intermittent claudication (IC) tend to walk slower and consume approximately 40% more oxygen during walking compared with healthy individuals. An unfavorable locomotion pattern has been suggested to explain this metabolic inefficiency. However, detailed knowledge of gait parameters in IC is lacking.

Methods: In a cross-sectional study, the gait pattern of newly diagnosed IC patients was compared with that of healthy controls. Spatiotemporal gait parameters such as step length and duration of stance phase were obtained by a photoelectric technique (OptoGait; Microgate, Bolzano, Italy). This system was previously found to have favorable concurrent validity and test-retest reliability characteristics. Parameters were determined during pain-free and painful treadmill walking at a comfortable self-determined walking pace. Each parameter was averaged on the basis of 80 steps.

Results: A total of 28 patients and 28 controls were examined. IC patients walked 1.2 km/h (−27%) slower than controls ($P < .001$), coinciding with a significantly shorter step length (−20%) and lower cadence (−11%). IC patients demonstrated a longer stance and double support phase, even before the onset of ischemic pain. Differences were also observed in segments of the stance phase, as a 14% shorter propulsion ($P < .001$) and 17% longer flat foot phase ($P < .001$) during painful walking were found. In considering the absolute duration of these stance phase segments, differences were found only for the flat foot time (Δ0.10 second; $P < .001$).

Conclusions: Patients with IC demonstrate an altered gait pattern compared with healthy controls. The most prominent differences were a prolonged relative and absolute duration of the flat foot position during the stance phase. This adaptation may be intuitive as an augmented arterial blood flow into skeletal muscles is allowed during a prolonged relaxation phase. Therefore, not only the lack of propulsion but also a gain of relaxation may explain these gait alterations. (J Vasc Surg 2017;66:515-22.)

The most common symptom of peripheral arterial disease (PAD) is intermittent claudication (IC), characterized by limb pain that is elicited by exercise and resolves after rest. Patients with IC demonstrate a limited walking distance, lower physical activity levels, diminished isokinetic distal muscle strength, and reduced quality of life.[1-4]

Patients with IC were found to consume more oxygen during walking compared with healthy controls.[5-7] Researchers have suggested various mechanisms that may be responsible for this increased oxygen requirement. For instance, an unfavorable gait pattern and a reduced recovery of potential energy through the pendulum-like mechanism were implicated.[8] Interestingly, some previous research excluded a reduced metabolic efficiency, whereas others reported on mitochondrial respiratory defects in PAD.[5,9]

Previous studies found that IC patients walk slower and have lower cadence rates and smaller stride lengths, mainly caused by an increased double limb support and stride time.[1,10] However, only basic spatiotemporal parameters have been evaluated in IC to date. Studying distinct subphases during the stance phase may also be interesting, particularly foot contact and toe-off (propulsion).[5,11] Calf muscles are known to contribute most to these subphases of the stance phase, and precisely the calves are considered the "functional end organs" in the lower extremity ischemia of IC patients.[12,13] Besides, calf muscle weakness has previously been described as a potential mechanism underlying IC gait adaptions.[14] Remarkably, a recent study did not demonstrate altered duration of calf muscle activation during walking in IC patients compared with healthy controls.[13] Nevertheless, spatiotemporal differences at this level are likely and may provide further insight into altered gait patterns. Further understanding might contribute to the development of rehabilitation strategies to restore the gait pattern and eventually walking distances, quality of life, and possibly even survival

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Author conflict of interest: none.

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The editors and reviewers of this article have no relevant financial relationships to disclose per the JVS policy that requires reviewers to decline review of any manuscript for which they may have a conflict of interest.

0741-5214

http://dx.doi.org/10.1016/j.jvs.2017.02.033

if one considers that reduced exercise capacity is the most powerful harbinger of long-term mortality in PAD.[15]

One study on potential beneficial effects of supervised exercise therapy (SET) failed to demonstrate any improvement in altered gait pattern.[16] However, consensus on which type of exercise leads to optimally improved walking ability is lacking.[17] As a consequence, current exercise protocols may not be tailored to confer significant improvements in walking patterns. Moreover, gait pattern outcomes may have been assessed inadequately, as previous research was mainly based on limited number of steps.[1,18] Fortunately, sensitive gait analysis systems have become available, allowing capture of continuous data during treadmill walking. These novel tools may optimize accuracy and generalizability of collected data on the gait pattern.

The primary aim of this study was to explore spatiotemporal gait parameters during continuous treadmill walking in IC patients and healthy controls. We hypothesized that patients with IC possibly demonstrate alterations of certain subphases of the stance phase.

ARTICLE HIGHLIGHTS

- **Type of Research:** Cross-sectional prospective nonrandomized controlled study
- **Take Home Message:** The 28 patients with claudication had a prolonged flat foot position during walking that was evident before onset of pain. This was significantly different from findings in 28 healthy controls.
- **Recommendation:** The authors suggest that changes in gait may be a compensatory mechanism that enhances arterial blood flow in patients with claudication.

METHODS

Participants. Patients were recruited from a population presenting with new-onset manifestations of IC at vascular surgery outpatient departments of three regional Dutch hospitals (Catharina Hospital, Eindhoven; Maxima Medical Center, Veldhoven; and St. Anna Hospital, Geldrop). According to standardized institutional protocols, potential patients underwent history taking and a physical examination including an ankle-brachial index (ABI) measurement during rest and after exercise. Individuals demonstrating typical symptoms of claudication in at least one lower leg and a <0.90 resting ABI or a >0.15 ABI drop after treadmill testing were eligible for study.[19] Inclusion criteria were >4 weeks of symptoms and the ability to walk without typical IC pain for ≥ 1 minute. Patients were excluded if they suffered from a comorbid condition possibly influencing gait pattern, such as lower extremity amputation, severe osteoarthritis (based on the American College of Rheumatology osteoarthritis criteria[20]), previous knee or hip prosthesis, severe cardiopulmonary problems (ie, Global Initiative for Chronic Obstructive Lung Disease stage $\geq$III or New York Heart Association class $\geq$III), neurologic diseases including peripheral polyneuropathy (eg, due to diabetes mellitus), Parkinson disease, stroke, previous surgery of lower extremities, use of walking aids or orthopedic shoes, or medication influencing walking pattern (eg, psychotropic medication). Patients who experienced rest pain, who suffered from chronic wounds, or who received more than five sessions of SET during the preceding 3 years were also excluded.

Control subjects of similar age, gender, height, and weight were recruited from family, friends, and hospital personnel. They all exhibited a >0.90 rest ABI and did not experience pain or limitations during walking. Exclusion criteria were as reported. Participants who were willing to undergo the study protocol were counseled before providing written informed consent. All procedures were approved by the Medical Ethical Committee of the Catharina Hospital, Eindhoven, The Netherlands.

Study protocol. Two researchers (L.N.M.G. and A.T.S.) were responsible for data collection and performed all measurements. Patients and controls were interviewed about general health, cardiovascular risk factors (smoking), and comorbid conditions. Height and weight allowed calculation of the body mass index. Leg length was determined with a tape measure in standing position and defined as the distance between the trochanter major of the hip and the inferior aspect of the lateral malleolus.[21]

After anthropometric measurements, participants walked for 10 minutes on a treadmill to get accustomed to its specifics.[22] Intervals of rest, if necessary, were allowed for IC patients. The preferred walking pace was then determined, defined as "walk at a pace that is comfortable and comparable to your outside walking."[22] The treadmill was started at 2.4 km/h. Speed was increased in increments of 0.1 km/h until self-selected comfortable walking speed was achieved. Speed was increased in increments until the fastest pace was attained and again decreased until the comfortable speed was reached once more. Gait pattern measurements were obtained at this final, self-selected comfortable walking pace. After 20 minutes of rest, IC patients were questioned as to whether the pain had completely resolved. If so, participants resumed treadmill walking. During 1 minute of painless walking, gait parameters were again obtained. Once IC patients experienced claudication, pain was determined using a 4-point claudication pain scale (1, minimal discomfort; 2, moderate pain; 3, intense pain; 4, unbearable pain).[23] Gait parameters were obtained for 1 minute after pain moved from grade 2 to grade 3.

Control subjects underwent the same measurements just once (ie, pain-free trial). All participants walked barefoot on a flat treadmill to exclude differences based on variable footwear.

Gait pattern. Spatial and temporal gait parameters were collected using an OptoGait Photoelectric Cell System (Microgate, Bolzano, Italy). This instrument consists of two bars of 1 meter each, a transmitting and receiving unit, respectively. Both bars contain 96 LED diodes, 1 cm apart and 3 mm above floor level, that are positioned onto the side bars of the treadmill (Fig 1). Parameters are determined when LED diodes are interrupted by one of two feet during walking. Data were sampled at a 1000 Hz frequency and saved on a laptop (OptoGait version 1.9.9.0 software; Mircogate). The system is validated for spatiotemporal gait parameters on a treadmill and was found to have a strong concurrent validity and test-retest reliability as demonstrated in various populations including healthy adults and patients after stroke or knee arthroplasty.[24,25] Moreover, reported minimum detectable changes were several times smaller than previously described differences in gait parameters of IC patients.

The following parameters were obtained: walking speed; cadence; gait cycle duration; step length; step time; duration of single and double limb support; swing and stance phase duration; and contact, flat foot, and propulsive phases (Fig 2). Step length was defined as the distance from heel contact of the first foot to heel contact of the subsequent contralateral foot.

Statistical analysis. Sample size calculation including an α of .01 and a β of .80 was based on both a spatial (stride length difference of 15 cm) and temporal (percentage stance phase difference of 2%) outcome variable and revealed a sample size of 25 and 14 subjects per group, respectively, to realize a statistically significant difference between both groups.[11]

Analyses and calculations of the data generated by the OptoGait software were performed in a customized program that was created in MATLAB R2012a (MathWorks, Natick, Mass). Eighty representative steps were obtained from each participant. Mean values and standard deviations were calculated for individual parameters per leg. In IC patients, the most symptomatic leg as based on the patient's history was considered the index leg. In healthy controls, the index leg was randomly selected. SPSS 20.0 (IBM, Armonk, NY) was used for statistical analysis. Demographic characteristics were expressed as percentages or group means and standard deviations. Differences between patients and controls were studied. In addition, evaluation within the patient group was performed. The symptomatic leg (eg, index leg) was compared with the asymptomatic leg (eg, asymmetry), and the index leg was compared during the pain-free and painful 1-minute measuring period. Pearson χ^2 and Fisher exact tests were used for analysis of categorical variables, whereas an independent samples and paired *t*-tests analyzed continuous variables. Variables that lacked normal distribution were expressed as median and corresponding interquartile ranges. Mann-Whitney *U* tests were used to compare these variables. Pearson correlation coefficients (ρ) were calculated to explore relations between spatiotemporal parameters and clinical determinants (ie, walking speed and ABI values). Statistical significance was set at $P < .01$ to control for multiple testing (type I error rate).

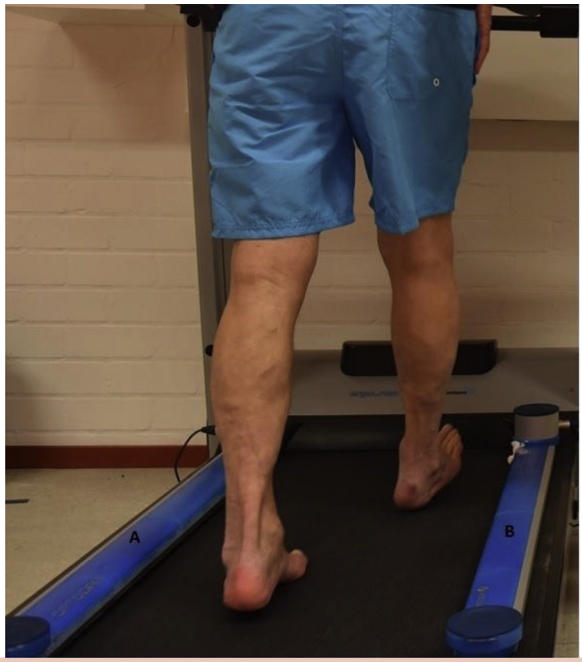

Fig 1. Study setup including the OptoGait system. The transmitting (*A*) and receiving (*B*) bars are positioned on both side bars of a treadmill. Spatiotemporal parameters are obtained by interruptions in the LED signal when a subject passes between the bars.

RESULTS

Study populations. The study population consisted of 28 IC patients and 28 controls of similar age, gender distribution, height, weight, and leg length (Table I). The rate of hypertension, however, was higher in the IC group. ABIs of patients during rest and after treadmill walking were 0.64 and 0.35, respectively. Almost half (n = 13 [46%]) of the IC patients had unilateral complaints.

Gait characteristics of IC patients and controls. The IC patients walked at a 1.2 km/h slower pace (IC patients, 3.3 km/h; controls, 4.5 km/h; $P < .001$; Table II), coinciding with a 24% shorter step length (IC patients, 49.2 cm; controls, 61.3 cm; $P < .001$), an 11% lower cadence (IC patients, 111 steps/min; controls, 122 steps/min; $P < .001$), and a 14% longer contact time (IC patients, 0.74 second; controls, 0.65 second; $P < .001$).

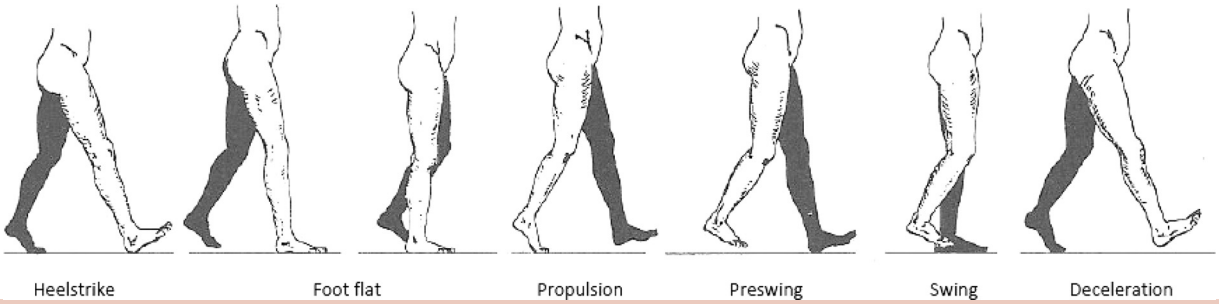

Fig 2. Phases of the normal gait cycle. The gait cycle is divided into the stance phase and swing phase. The stance phase, which is defined as the heel to toe contact of the foot, accounts for around 60% of the gait cycle; the swing phase accounts for the remaining 40%. The stance phase can be divided into heel strike, the first contact of the heel with the floor; foot flat phase, the period during which the complete foot is in contact with the ground; and the propulsion phase, the termination of stance phase, which starts when the heel leaves the ground and ends with complete set-off of the tip of the foot. (Adapted from Schafer RC. Clinical biomechanics. Baltimore: Williams & Wilkins; 1987. Used with permission.)

The relative duration of the single support phase was also significantly shorter in IC patients compared with controls (Δ2.3% and Δ3% for pain-free and painful ambulation, respectively). Moreover, the relative duration of the double support phase was significantly longer (Δ4.3% and Δ5% for pain-free and painful ambulation, respectively). IC patients also had an evidently longer lasting foot flat phase (pain free, Δ4.9% [$P = .007$] and painful, Δ7.4% [$P < .001$]) and shorter propulsive phase compared with controls (pain free, Δ4.1% [$P = .016$] and painful, Δ6.5% [$P < .001$]). Reported differences between IC patients and controls increased during painful walking (Table II). Despite the difference in the relative duration of the propulsive phase, no difference was found in absolute propulsion time between IC patients and controls.

Gait characteristics during pain-free and painful walking in IC patients. Differences were found only in the subphases of the stance phase when pain-free walking and painful walking in IC patients were compared. Once claudication pain was manifested, the relative duration of flat foot increased significantly from 54.4% to 56.8% ($P = .002$), whereas the relative contribution of propulsion decreased from 34.0% to 31.6% ($P < .001$). In addition, during painful walking, mean flat foot time increased by 0.02 second ($P < .001$), whereas mean propulsion time decreased by 0.02 second ($P < .001$).

No asymmetry in gait parameters was found when comparing the index leg (ie, most symptomatic IC leg) with the contralateral leg, for both the pain-free and painful sessions (data not shown). A subanalysis of the unilateral IC patients (n = 13) also revealed no significant differences between both legs of IC patients.

Correlations. No significant or clinically relevant correlations were found between ABI values and any of the gait parameters. For the analyses between walking speed and gait parameters, two parameters were found to correlate with walking speed. In healthy controls, walking speed was moderately correlated with relative duration of the propulsion phase ($\rho = .541$; $P = .005$). In contrast, no correlation was found for this variables in

Table I. Demographics of intermittent claudication (*IC*) patients and controls undergoing gait analysis

Characteristic	IC patients (n = 28)	Controls (n = 28)	*P* value
Gender, male	20 (71)	16 (57)	.27
Age, years	68 (6.8)	68 (6.7)	.75
Height, m	1.70 (0.08)	1.69 (0.08)	.64
Weight, kg	80 (13)	75 (11)	.10
Leg length, cm	80.6 (5.2)	80.5 (4.5)	.92
Index leg, left[a]	13 (46)	14 (50)	.79
ABI of index leg			
Rest	0.64 (0.19)	1.08 (0.16)	<.001
After treadmill walking	0.35 (0.16)	—	
Duration of symptoms, months	17 (16)	—	
Unilateral or bilateral complaints, unilateral	13 (46)	—	
BMI, kg/m^2	28.6 (4.9)	26.4 (4.7)	.10
Smoking			
Current smoker	14 (50)	3 (11)	.02
Former smoker	11 (39)	14 (50)	
Never smoker	3 (11)	11 (39)	
Hypertension	19 (68)	6 (21)	<.001
Diabetes mellitus	7 (25)	1 (4)	.05
Cardiac disease[b]	8 (29)	2 (7)	.08
Transient ischemic attack	2 (7)	1 (4)	1.00
COPD	4 (14)	3 (11)	1.00
Osteoarthritis	4 (14)	1 (4)	.35

ABI, Ankle-brachial index; *BMI,* body mass index; *COPD,* chronic obstructive pulmonary disease.
Categorical variables are presented as number (%). Continuous variables are presented as mean (standard deviation).
[a]The index leg is the most symptomatic leg in IC patients and randomly selected for controls.
[b]Cardiac disease included coronary artery disease, arrhythmia, and pacemaker.

Table II. Gait characteristics of intermittent claudication (*IC*) patients during painless and painful walking compared with age-matched controls

Variable	IC patients (n = 28)		*P* value[a]	Controls (n = 28)	*P* value[b]	*P* value[c]
	Pain free	Painful				
Walking speed, km/h	3.3 (0.6)			4.5 (0.8)	<.001	
Step length, cm	49.2 (8.4)	50.0 (8.7)	.03	61.3 (9.8)	<.001	<.001
Stride length, cm	99.6 (3.0)	99.9 (3.0)	.62	123.6 (19.5)	<.001	<.001
Cadence, steps/min	111 (7.9)	110 (8.0)	.73	122 (9.6)	<.001	<.001
Contact time, seconds	0.74 (0.06)	0.74 (0.07)	.75	0.65 (0.1)	<.001	<.001
Single support, %	32.4 (2.5)	31.7 (2.9)	.01	34.7 (2.2)	.001	<.001
Double support, %	35.3 (4.3)	36.0 (4.7)	.03	31.0 (4.4)	.001	<.001
Stance phase, %	67.7 (2.3)	67.6 (2.3)	.88	65.7 (2.5)	.003	.004
Swing phase, %	32.3 (2.3)	32.4 (2.3)	.97	34.3 (2.5)	.003	.003
Contact phase, %	11.6 (2.6)	11.6 (3.7)	.88	12.4 (2.5)	.227	.36
Contact phase, seconds	0.08 (0.02)	0.09 (0.03)	.78	0.08 (0.02)	.39	.42
Foot flat phase, %	54.4 (7.1)	56.8 (7.0)	.002	49.5 (6.1)	.007	<.001
Foot flat phase, seconds	0.40 (0.07)	0.42 (0.07)	.001	0.32 (0.06)	<.001	<.001
Propulsive phase, %	34.0 (6.5)	31.6 (5.9)	<.001	38.1 (5.9)	.02	<.001
Propulsive phase, seconds	0.25 (0.05)	0.23 (0.04)	.001	0.25 (0.04)	.81	.16

Step length: distance between heels of two subsequent feet. Stride length: distance between the first contact of the heel with the floor and the second contact of the same heel. Contact time: time when the foot is in contact with the ground. Single support: time when only one foot touches the ground. Double support: sum of two partial double supports of one gait cycle. Stance phase: similar to the contact time but expressed as percentage of one gait cycle. Contact phase: moment between first contact of the heel (eg, heel strike) and foot flat. Foot flat: moment that the foot completely touches the ground. Propulsive phase: moment from lifting the heel to complete set-off of the tip of the foot (Fig 2).
Data are presented as mean values (standard deviation).
[a]Paired *t*-test: pain free vs painful within group of IC patients.
[b]Independent samples *t*-test: pain free vs control.
[c]Independent samples *t*-test: painful vs control.

IC patients ($\rho = .187$; $P = .341$). Foot flat time, on the other hand, was significantly correlated to walking speed in both IC patients and controls (Fig 3).

DISCUSSION

The purpose of this study was to explore spatiotemporal gait parameters in patients with IC during continuous treadmill walking. This is the first study investigating individual phases of the stance phase in this population of patients using this approach. Patients with IC walked 27% slower and were longer in stance phase than healthy controls. In addition, distinct differences were present in the various different segments of the stance phase. A 14% decrease in propulsion duration and a 17% increase in foot flat duration were observed in IC patients. Interestingly, these alterations were already present even before claudication pain started.

Previous research reported contrasting findings of altered gait pattern in patients with IC. Most studies observed differences in percentage of stance phase and double support, walking speed, and cadence that are in line with our results.[10,26,27] Others reported no effect of claudication on several temporal and spatial gait measures.[28,29] However, relatively small samples sizes and suboptimal monitoring techniques, including the use of papered walkways with stopwatch recording, might explain the lack of differences in these studies, as study populations were comparable with our IC patients in terms of age and ABIs.[28,29]

A unique aspect of this study is the assessment of gait parameters during continuous treadmill walking. We based our results on averaging data obtained during 80 steps, whereas others reported on just a couple of steps during a short 4- to 7-meter walk.[1,10] In the study of McCully et al, patients walked on a treadmill until a sufficient pain level was obtained, followed by gait measurements during overground walking.[30] Our treadmill-based methodology also allowed capture of data immediately after the pain threshold was reached, thereby excluding confounding due to possible recovery processes. Based on this optimized and standardized methodology, we are confident that the results of this study truly reflect alterations in gait pattern that occur in patients with IC.

Determining differences in gait patterns between IC patients and controls is deemed important for several reasons. Walking is one of the most important daily activities of human life. From the very first step that is made, individual gait patterns are optimized as walking is the most economical means of locomotion. Gait speed is known to be an independent predictor of all-cause mortality, and gait speed differences between 0.36 km/h and

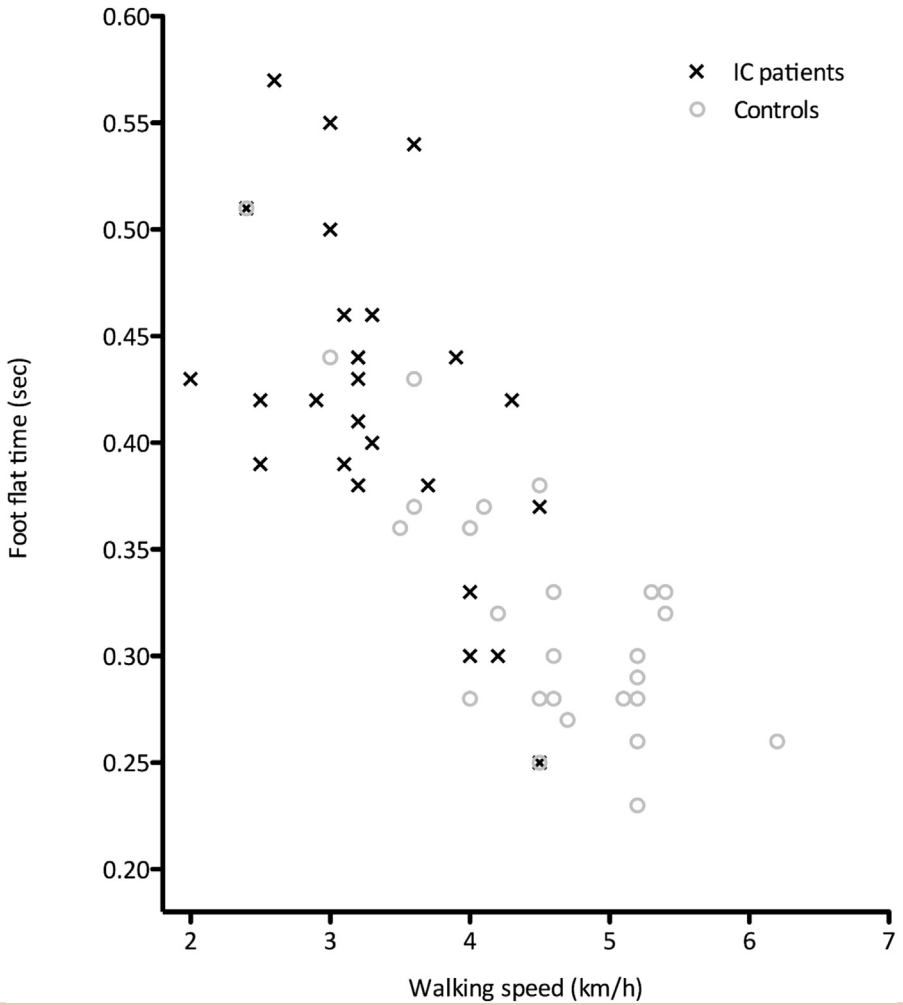

Fig 3. Scatterplot of the time for flat foot and walking speed. Intermittent claudication (*IC*) patients: *r*, −0.565 ($P = .002$); controls: *r*, −0.784 ($P < .001$).

0.72 km/h are termed clinically relevant.[31,32] Interestingly, speed differences in this study were at least twice as large (1.2 km/h). Biomechanical gait alterations might contribute to the slower walking speed of IC patients. Further understanding and subsequent improvement of the gait pattern might therefore contribute to the prognosis of IC patients. The 14% difference in propulsion between painful walking in IC patients and controls revealed a Cohen *d* effect size of 0.48, which may be interpreted as medium. So, even initiative small differences seem to have a substantial impact.

The precise explanation for these gait changes in IC is still unknown. There may be a pathophysiologic mechanism, related to the lower blood flow of IC patients, that partly explains the gait changes observed in patients with IC.[33] This study showed that IC patients spend a significantly longer percentage in flat foot position, whereas no differences were found in absolute propulsion time. These findings are in line with a recent study that also demonstrated no difference in relative calf muscle activation.[13] Hence, the additional time per gait cycle as a consequence of the slower walking pace in IC is completely used for the flat foot phase. This phenomenon may reflect an intuitive adaptation because skeletal muscle blood flow mainly occurs during the relaxation phase of dynamic exercise. Moreover, the relaxation period in part determines the magnitude of arterial inflow.[34] However, it might also be a strategy to minimize oxygen use by a prolonged relaxation time. Nevertheless, analogous to walking stops when claudication pain is maximized, IC patients have already "discontinued" walking for a longer period during every step as a means to allow sufficient blood inflow or to save use of oxygen. This hypothesis may also explain why IC patients take fewer rather than shorter steps when claudication pain develops.[26] In addition, altered gait parameters might also be explained by the difference in walking speed, as flat foot time correlated with walking speed for both healthy controls and IC patients. Although gait adaptations in response to ischemic pain cannot be ruled out yet, the current research may fuel the search for novel training modalities of SET aimed at improving

gait pattern. Strategies to improve walking speed might be a valuable starting point. Walking at a higher speed during SET might increase training efficiency as patients are thought to reach their claudication threshold earlier by superseding the compensatory mechanism. On the other hand, a higher walking speed might also be advantageous in terms of walking economy because IC patients are known to walk at a velocity below the optimal point of energy costs.[35] Future studies may focus on the value of treadmill training on a higher pace. Moreover, efforts to increase calf muscle strength during SET could also be vital to improve propulsion and eventually the gait pattern of IC. This might be beneficial from the perspective of the increased risk of falling as well. Last, the value of rollover footwear (ie, MBT footwear) might be of particular interest for IC patients as previous research described reduced ankle plantar flexion moments during propulsion, without change in metabolic costs or walking speed.[36]

Some study limitations need to be addressed. First, we included only participants without additional comorbidities (eg, osteoarthritis or previous lower limb surgery) potentially affecting the gait pattern. Therefore, the present findings were obtained from IC patients who were in relatively good condition. As a consequence, the results might be overestimated in favor of a relatively normal gait pattern. Conversely, results may not be generalized to IC patients with numerous comorbid conditions. Participants with diabetes mellitus were not excluded, and one study reported lower ankle generative mechanical work in patients with diabetes mellitus, even in the absence of diabetic neuropathy. As diabetes mellitus was more prevalent among IC patients, propulsion is possibly underestimated in the IC group. Second, we captured data during treadmill walking, which is not necessarily similar to overground walking, although Riley et al reported identical kinematic and kinetic parameters during treadmill and overground gait.[37] It is thus thought that movement analysis during treadmill walking reveals valid results, all the more so when other advantages of treadmill-based protocols are taken into account. One might question the influence of a treadmill protocol regarding the lack of asymmetry in spatiotemporal parameters, especially in unilateral IC patients, as found in this study. However, Gardner et al also found no asymmetry in IC patients during an overground walking protocol.[10] Third, this research included spatiotemporal analyses only. As data on kinematics, kinetics, and surface electromyography were not included, we were not able to provide additional views from alternative perspectives. However, our findings might serve as a starting point for further research to elucidate underlying mechanisms of impaired walking function in patients with IC, for instance, the role of muscle strength in gait alterations of IC.

CONCLUSIONS

Patients with IC demonstrate altered spatiotemporal gait parameters during treadmill walking that already occur before the actual onset of claudication pain. This gait pattern is characterized by a slower walking pace and longer double support phase and stance phase. The prolonged flat foot phase might be a possible compensatory disease-related mechanism contributing to this reduced walking speed.

We would like to thank Lode B.V. Groningen and Procare B.V. Groningen for providing a treadmill and Microgate Italy and Procare B.V. Groningen for the OptoGait system. We would like to thank Ingeborg Trul, human movement scientist at Procare B.V., for her technical support. Last, we greatly appreciated the help of Jos Swinkels, nurse practitioner at St. Anna Hospital Geldrop, for the recruitment of study participants.

AUTHOR CONTRIBUTIONS

Conception and design: LG, FB, KM, JT
Analysis and interpretation: LG, AS, MS, FB, KM
Data collection: LG, AS, EC, FB
Writing the article: LG, MS
Critical revision of the article: AS, MS, EC, FB, KM, JT
Final approval of the article: LG, AS, MS, EC, FB, KM, JT
Statistical analysis: LG, KM
Obtained funding: Not applicable
Overall responsibility: JT

REFERENCES

1. Crowther RG, Spinks WL, Leicht AS, Quigley F, Golledge J. Relationship between temporal-spatial gait parameters, gait kinematics, walking performance, exercise capacity, and physical activity level in peripheral arterial disease. J Vasc Surg 2007;45:1172-8.
2. Lauret GJ, Fokkenrood HJ, Bendermacher BL, Scheltinga MR, Teijink JA. Physical activity monitoring in patients with intermittent claudication. Eur J Vasc Endovasc Surg 2014;47:656-63.
3. Camara LC, Ritti-Dias RM, Meneses AL, D'Andrea Greve JM, Filho WJ, Santarem JM, et al. Isokinetic strength and endurance in proximal and distal muscles in patients with peripheral artery disease. Ann Vasc Surg 2012;26:1114-9.
4. Mays RJ, Casserly IP, Kohrt WM, Ho PM, Hiatt WR, Nehler MR, et al. Assessment of functional status and quality of life in claudication. J Vasc Surg 2011;53:1410-21.
5. Marconi C, Ferretti G, Anchisi S, Catalano M, Scandale G, Antico A, et al. Energetics of walking in patients with peripheral arterial disease: a proposed functional evaluation protocol. Clin Sci (Lond) 2003;105:105-11.
6. Gardner AW, Ritti-Dias RM, Stoner JA, Montgomery PS, Scott KJ, Blevins SM. Walking economy before and after the onset of claudication pain in patients with peripheral arterial disease. J Vasc Surg 2010;51:628-33.
7. Womack CJ, Sieminski DJ, Katzel LI, Yataco A, Gardner AW. Improved walking economy in patients with peripheral arterial occlusive disease. Med Sci Sports Exerc 1997;29:1286-90.

8. Cavagna GA, Thys H, Zamboni A. The sources of external work in level walking and running. J Physiol 1976;262:639-57.
9. Pipinos II, Judge AR, Selsby JT, Zhu Z, Swanson SA, Nella AA, et al. The myopathy of peripheral arterial occlusive disease: part 1. Functional and histomorphological changes and evidence for mitochondrial dysfunction. Vasc Endovascular Surg 2007;41:481-9.
10. Gardner AW, Forrester L, Smith GV. Altered gait profile in subjects with peripheral arterial disease. Vasc Med 2001;6:31-4.
11. Astephen JL, Deluzio KJ. Changes in frontal plane dynamics and the loading response phase of the gait cycle are characteristic of severe knee osteoarthritis application of a multidimensional analysis technique. Clin Biomech (Bristol, Avon) 2005;20:209-17.
12. Winter DA. Biomechanical motor patterns in normal walking. J Mot Behav 1983;15:302-30.
13. Gommans LN, Smid AT, Scheltinga MR, Brooijmans FA, van Disseldorp EM, van der Linden FT, et al. Altered joint kinematics and increased electromyographic muscle activity during walking in patients with intermittent claudication. J Vasc Surg 2016;63:664-72.
14. Koutakis P, Johanning JM, Haynatzki GR, Myers SA, Stergiou N, Longo GM, et al. Abnormal joint powers before and after the onset of claudication symptoms. J Vasc Surg 2010;52:340-7.
15. Leeper NJ, Myers J, Zhou M, Nead KT, Syed A, Kojima Y, et al. Exercise capacity is the strongest predictor of mortality in patients with peripheral arterial disease. J Vasc Surg 2013;57:728-33.
16. King S, Vanicek N, Mockford KA, Coughlin PA. The effect of a 3-month supervised exercise programme on gait parameters of patients with peripheral arterial disease and intermittent claudication. Clin Biomech (Bristol, Avon) 2012;27:845-51.
17. Fakhry F, van de Luijtgaarden KM, Bax L, den Hoed PT, Hunink MG, Rouwet EV, et al. Supervised walking therapy in patients with intermittent claudication. J Vasc Surg 2012;56:1132-42.
18. McCully K, Leiper C, Sanders T, Griffin E. The effects of peripheral vascular disease on gait. J Gerontol A Biol Sci Med Sci 1999;54:B291-4.
19. Gardner AW, Skinner JS, Cantwell BW, Smith LK. Progressive vs single-stage treadmill tests for evaluation of claudication. Med Sci Sports Exerc 1991;23:402-8.
20. Johns Hopkins Arthritis Center. ACR clinical classification criteria for osteoarthritis of hip 2013. Available at: http://www.hopkinsarthritis.org/physician-corner/education/arthritis-education-diagnostic-guidelines/#class_hip. Accessed June 10, 2016.
21. Vaughan CL, Davis BL, O'Connor JC. Dynamics of human gait. 2nd ed. Cape Town, South Africa: Kiboho; 1999.
22. Van de Putte M, Hagemeister N, St-Onge N, Parent G, de Guise JA. Habituation to treadmill walking. Biomed Mater Eng 2006;16:43-52.
23. ACSM guidelines for exercise testing and prescription. Philadelphia: Wolters Kluwer/Lippincott Williams & Wilkins; 2014.
24. Lienhard K, Schneider D, Maffiuletti NA. Validity of the Optogait photoelectric system for the assessment of spatiotemporal gait parameters. Med Eng Phys 2013;35:500-4.
25. Lee MM, Song CH, Lee KJ, Jung SW, Shin DC, Shin SH. Concurrent validity and test-retest reliability of the OPTOGait Photoelectric Cell System for the assessment of spatiotemporal parameters of the gait of young adults. J Phys Ther Sci 2014;26:81-5.
26. Mockford KA, Vanicek N, Jordan A, Chetter IC, Coughlin PA. Kinematic adaptations to ischemic pain in claudicants during continuous walking. Gait Posture 2010;32:395-9.
27. Scherer SA, Bainbridge JS, Hiatt WR, Regensteiner JG. Gait characteristics of patients with claudication. Arch Phys Med Rehabil 1998;79:529-31.
28. Scherer SA, Hiatt WR, Regensteiner JG. Lack of relationship between gait parameters and physical function in peripheral arterial disease. J Vasc Surg 2006;44:782-8.
29. Gardner AW, Montgomery PS, Ritti-Dias RM, Forrester L. The effect of claudication pain on temporal and spatial gait measures during self-paced ambulation. Vasc Med 2010;15:21-6.
30. McCully KK, Landsberg L, Suarez M, Hofmann M, Posner JD. Identification of peripheral vascular disease in elderly subjects using optical spectroscopy. J Gerontol A Biol Sci Med Sci 1997;52:B159-65.
31. Toots A, Rosendahl E, Lundin-Olsson L, Nordstrom P, Gustafson Y, Littbrand H. Usual gait speed independently predicts mortality in very old people: a population-based study. J Am Med Dir Assoc 2013;14:529.e1-6.
32. Bohannon RW, Glenney SS. Minimal clinically important difference for change in comfortable gait speed of adults with pathology: a systematic review. J Eval Clin Pract 2014;20:295-300.
33. Sorlie D, Myhre K. Lower leg blood flow in intermittent claudication. Scand J Clin Lab Invest 1978;38:171-9.
34. Radegran G, Saltin B. Muscle blood flow at onset of dynamic exercise in humans. Am J Physiol 1998;274(Pt 2):H314-22.
35. Womack CJ, Sieminski DJ, Katzel LI, Yataco A, Gardner AW. Oxygen uptake during constant-intensity exercise in patients with peripheral arterial occlusive disease. Vasc Med 1997;2:174-8.
36. Forghany S, Nester CJ, Richards B, Hatton AL, Liu A. Rollover footwear affects lower limb biomechanics during walking. Gait Posture 2014;39:205-12.
37. Riley PO, Paolini G, Della Croce U, Paylo KW, Kerrigan DC. A kinematic and kinetic comparison of overground and treadmill walking in healthy subjects. Gait Posture 2007;26:17-24.

Submitted Oct 9, 2016; accepted Feb 10, 2017.